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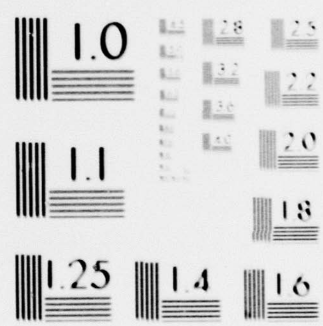

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STEADY STATE AND RF PROPERTIES OF

PROXIMITY EFFECT WEAK LINKS

R.P. McNamara, Bell Laboratories, Indian Hill, Naperville, Illinois and

J.E. Mercereau, California Institute of Technology, Pasadena, California

contract to

Abstract

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A detailed experimental examination of the dc critical supercurrent density, j_c, and the microwave (nonzero voltage) supercurrent, j_μ, has been made in proximity effect thin film weak links at temperatures above the transition temperature of the link material. These results were correlated with measured dimensional and superconducting parameters of the thin films and the link via a Ginzberg-Landau (GL) formalism. In the steady state, j_c, was found to be adequately described by a one dimensional GL formalism similar to that of Likharev and Yakobson but with De Gennes boundary conditions on the order parameter applied at each interface. However, j_μ decreases exponentially with increasing voltage and can be interpreted in terms of an interference modulation of the induced pair density within the link at the Josephson frequency.

Introduction

This paper correlates the quantum electronic behavior of a particular class of superconducting thin film weak link, the proximity effect link,[1] with the dimensional and superconducting parameters of the link. The proximity effect link is similar to the variable thickness link[2] in that both have well-defined dimensional geometries. However the proximity effect link is comprised of a superconductor whose intrinsic transition temperature $T_{s'}$ differs from that of the adjoining material T_s, and usually $T_{s'} < T_s$. Consequently we will characterize these links as S/S'/S links. Measurements of thin film parameters such as resistivity ρ, coherence length ξ, penetration depth λ, etc. for both S and S' were reported earlier.[3] These measured parameters are herein correlated with the dc supercurrent density j_c of proximity weak links fabricated in the films for the temperature range $T > T_{s'}$. The microwave supercurrent, j_μ, was also experimentally determined and for $T > T_{s'}$ was found to be both frequency and voltage dependent. This dependence will be shown to be functionally equivalent to voltage stimulated pair breaking in S'.

Experimental Results

Measurements of the critical current, I_c, were performed by a standard four terminal technique. Considerable care was taken with magnetic shielding and field compensation for all measurements, since these weak links display a nearly ideal magnetic modulation of the critical current. The critical current, I_c, was measured as a function of temperature T, bridge length L, width w, and thickness t for several materials and structures. Thin films and layered film structures were fabricated by high vacuum electron beam deposition onto sapphire substrates. For the layered films, material A was evaporated sequentially in high vacuum directly on top of material B and will be indicated by (A/B). The resulting layered structures were composed of films thinner than their respective coherence lengths with no intervening oxide layer so that the composite superconductivity of the film is well characterized. Independent measurements of the relevant superconducting parameters such as ξ, λ, resistivity ρ, and transition temperature T_s were made for both the S and S' thin films and layered structures[3] in order to facilitate a direct comparison to theory. Layered thin films of (Ta/Hf), (Ta/Ti), and (Sn/Au) as well as ion (Cu or Fe) implanted Ta films have been studied. S/S'/S weak links have been fabricated with all of these materials. The details of the weak link fabrication are outlined in earlier work.[1,3]

In general, for the longer links ($L \geq 2$ μm) we find that the critical current density can be completely characterized by a one-dimensional GL theory utilizing the actual superconducting parameters, ξ, λ, ρ, etc. of the films. Systematic deviations from the simplest GL description will be discussed. As might have been hoped, there is no apparent residual dependence on specific material, substrate, width, or thickness of film.

The results shown herein are typical for all of the weak links in all materials. The temperature, $T_{s'}$, is the superconducting transition temperature of the link S' region <u>if isolated</u> from S. As indicated in Fig. 1, supercurrent appears for $T > T_{s'}$.

Figure 1 shows typical critical current data for three Ta/Ti weak links ($W = 25$ μm, $t = 23$ nm) as a function of length and temperature above and through $T_{s'}$. The curves also shown in Fig. 1 are the result of the calculation to be discussed. Below $T_{s'}$, the critical current gradually assumes a $(T_{s'} - T)^{3/2}$ dependence as reported earlier.[3]

The amplitude of the microwave supercurrent j_μ was experimentally determined by an examination of the microwave induced step structure[4] in the dc current-voltage (I-V) curve. These steps were investigated as a function of bridge length L, frequency ω, step number n, temperature T, dc voltage $V_o = \hbar\omega/2e$, and microwave voltage V_μ. The data on j_μ reported herein refer to the weakly coupled limit only; i.e., $T > T_{s'}$. Step width was determined from measurements of the differential resistance (dV/dI) of the I-V curve. For these links, the steps are very well defined and step width was identified as the current interval over which $dV/dI \leq 1/2$ normal state resistance R_n. An alternative definition of step width as the interval over which $dV/dI = 0$ did not change the data by more than 5%. Microwave voltage V_μ was determined by assuming a Bessel periodicity in step size, as in the RSJ model, and normalizing V_μ with respect to V_o at the first zero of the $n = 0$ step. Figure 2(a) shows the maximum amplitude of the $n = 1$ step (relative to I_c) as a function of frequency and link length.

Again, these results are typical of all links we have studied in that similar results are found for links of different material but with similar dimensions and critical current density. Specifically the data in Fig. 2 are for three Ta/Hf links of width ≈25 μm at $I_c = 20$ μA. In Fig. 2, the microwave voltage V_μ was adjusted so as to maximize the step amplitude. Figure 2(b) shows the maximum step amplitude as a function of step number, n, at a constant frequency (4 GHz) for the shortest ($L = 0.5$ μm) Ta/Hf link. In all cases, the relative amplitude of the step width was found to be nearly independent of T for $T > T_{s'}$ and $\hbar\omega/2eI_cR \geq 1$. All of the data on j_μ reported herein is within these limits and thus may not be directly comparable to variable thickness bridges of single material. The result of a simple RSJ calculation is shown in Fig. 2. A deviation from the simple RSJ model is observed with increasing frequency, bridge length, and step number.

Discussion of Steady State Results, j_c

To analyze the steady state data, a one-dimensional Ginzburg-Landau (GL) model similar to that of Likharev and Yakobson[2] (LY) was used to evaluate j_c for $T > T_{s'}$. In this analysis one modification was made to the model of LY which was the use of De Gennes boundary conditions[5] on the order parameter at each S/S' interface. It should be noted that the energy gap, Δ_s in the film adjacent to the link is depressed below $\Delta_{s\infty}$ due to proximity effects. This is in contrast to the rigid boundary condition used by LY which assumed that Δ in the film adjacent to the link is equal to the equilibrium value, $\Delta_{s\infty}$. If the rigid boundary conditions of LY are utilized to calculate j_c, along with the actual geometric length L of the link, the predicted critical current j_c is about an order of magnitude larger than experimentally observed. A first order correction[6] to this approximation is to assume that the effect length is somewhat greater than L. Our analysis attempts a more detailed correction by utilizing the De Gennes boundary conditions.

The LY model also assumes that the order parameter in the weakened region is a linear superposition of order parameters, differing in phase, induced from each of the boundary superconductors. This linear approximation is probably adequate only when the link length, L, is $\gg\xi_{s'}(T)$ so that no secondary boundary condition need be applied to either order parameter, except to vanish at infinity. Effectively, the cubic terms in the GL calculation are being ignored. One possible effect of this assumption will be considered later.

There is no simple closed form for the critical current, j_c,[7] using the LY analysis and De Gennes boundary conditions; however, it can be written in the following form:

$$j_c = \frac{3\sqrt{3}}{2}\ 0.9\ j_{GL}(T)\ \frac{8B^2}{(1 + (1 + B^2/2)^{1/2})^2}\ \exp\left(-L/\xi_{s'}(T)\right) \qquad (1)$$

This expression is functionally indentical to previous results;[2,6] but the parameter B^2 is a more complicated function than presented in References 2 and 6 because of the De Gennes boundary conditions. As previously shown,[2,6,7] the parameter j_{GL}, for $T > T_{s'}$, can be related to ξ and λ for $T < T_{s'}$. The parameters $\xi(0)$ and $\lambda(0)$ are analytically defined for $T < T_{s'}$ by $\xi(T) = \xi(0)(1 - t)^{-1/2}$ and $\lambda(T) = \lambda(0)(1 - t)^{-1/2}$ where $t = T/T_{s'}$. With this definition, the parameter j_{GL} for $T > T_{s'}$ becomes $j_{GL} = \phi_0[3\sqrt{3}\ \pi\ \mu_0\xi_{s'}(0)\ \lambda^2\ (0)]^{-1}(t - 1)^{3/2}$, where ϕ_0 and μ_0 are respectively the flux quantum and the permeability. In evaluating Eqn (1), the <u>decay</u> length $\xi_{s'}$ (for $T > T_{s'}$) has been related to the <u>coherence</u> length in S' ($T < T_{s'}$), by the relation:[7,8]

$$\xi_{s'}(T > T_{s'}) = 0.9\ \xi_{s'}(0)(t - 1)^{-1/2} \quad , \qquad (2)$$

where $\xi_{s'}(0)$ is a measured quantity.[3]

The parameter B^2 contains the influence of the boundary conditions and can be written in terms of the density of states at the Fermi surface, N, interaction potential, V, and transition temperatures as: $B^2 = B_o^2[(NV)_{s'}^2 T_s/(NV)_s^2 T_{s'}] \tanh^2 C$. The parameter C must be determined analytically as will be indicated. In the limit where $T_{s'} \lesssim T_s$, $B_o^2 = (T_s - T)/(T - T_{s'})$, while for $T_{s'} << T_s$, $B_o^2 = 0.33\, T_s/(T - T_{s'})$. The product (NV) was evaluated from the BCS relationship $(NV)^{-1} = \ln(1.14\, \theta_D/T_{s',s})$, and the Debye temperature θ_D was taken to be a spatially weighted average value for the layered films. The parameter C comes from evaluating the following expression numerically:[7]

$$\sinh 2C[1 + 1/2\, B^2/\{1 + (1 + 1/2\, B^2)^{1/2}\}] = 2(\rho_{s'}/\rho_s)\{\xi_{s'}(T)/\xi_s(T)\} .$$

For the rigid boundary conditions of LY, $B^2 = B_o^2$.

Equation (1) has been evaluated by using experimentally determined values of $\xi(0)$, $\lambda(0)$, resistivity, and transition temperature for the S and S' films.[3] In relating measurement to theory, it was assumed that the current through the link was distributed uniformly. This assumption was based on the experimental observations that: 1) superconducting ground planes placed directly over the link did not affect I_c; 2) the magnetic modulation of I_c was nearly the ideal Josephson diffraction effect; and, 3) j_c was found experimentally to be independent of w until flux trapping occurs. The critical current density, j_c, was then calculated from I_c by $j_c = I_c(wt)^{-1}$, where t is the film thickness.

Typical results are shown in Fig. 1, these data are for three links which differ only in their length. Note, that Expression 1 now has no adjustable parameters since experimental values are utilized for all parameters. We estimate that the overall absolute accuracy of the calculation is about a factor of 2 due to the uncertainty in all the separate measurements. In general, good agreement (within a factor of 2) in both absolute magnitude and temperature dependence between theory and experiment has been found for all of the longer ($L \gtrsim 1$ μm) links which we have studied. We interpret these results as indicating the essential correctness of the theory[2] and the appropriateness of the De Gennes boundary conditions for these circumstances.

However, for the shorter links ($L < 1$ μm) the measured amplitude of j_c always systematically decreases as the length decreases although the temperature dependence of j_c is correctly described by Eqn. (1). For a given length, the ratio between theoretical j_c(GL), and experimental j_c(exp) critical current is roughly independent of temperature (both above and below $T_{s'}$). The insert in Fig. 1 shows j_c(exp) as a function of length — normalized to the value for the longest link. These data are typical for all links which differ only in length. The relative accuracy of such data is ±10% and control experiments indicate that this length dependence is probably not due to a systematic experimental error. We take it as evidence for a length dependence in j_c in addition to that accounted for by the calculations. One possible interpretation is that the induced order parameter in S' cannot simply be approximated by the linear superposition of two independent order parameters when the bridge length (spacing between the two S/S' boundaries) becomes comparable with the decay length $\xi_{s'}(T)$. For this case, higher order corrections must be made and the effects of a second boundary must be added to each order parameter. Such calculations are in progress.

Discussion of Nonsteady State Results

In the finite voltage state, quasi-particle current also occurs in S'. The effect of these currents can be approximated by the resistively shunted junction (RSJ) model.[9] We have used this model to calculate the magnitude of the "step" induced in the dc I-V characteristics when irradiated with microwave radiation. Below about 1 GHz, the RSJ model with the microwave supercurrent amplitude j_μ equal to j_c has been found[6,7,9] adequate to describe the experimental results. However as Fig. 2 indicates, when $T > T_{s'}$ and for frequency above ~1 GHz, amplitude of j_μ begins to decrease significantly from that expected from a simple RSJ analysis, especially for longer links. At higher frequency (~10 GHz) j_μ usually again increases[3] and can be larger than j_c as in the Dayem-Wyatt[10] effect. Microwave response has been observed[11] to above 250 GHz in these links at lower temperature. However, these higher frequency effects are material dependent. This paper will concentrate on the more systematic low frequency data in the temperature range $T > T_{s'}$.

From this data we have attempted to construct a simple empirical expression for j_μ. From an analysis of all of our data from 1-4 GHz it appears that an empirical dependence of the form $|j_\mu| = j_c \exp(-\bar{V}/V^*)$, is adequate to describe these results. $\bar{V}$, the RMS voltage, is $\bar{V} = [(nV_0)^2 + 1/2\, V_\mu^2]^{1/2}$ and V^* is a length dependent constant for all links, where V^* (volts) = $10^{-5}\, L^{-1}$ (μm). This result was found to fit these data ($T > T_{s'}$) for many different links of differing dimensions and material up to ≈4 GHz. The curves shown in Fig. 2 are the result of an RSJ calculation including this empirical amplitude dependence of $|j_\mu|$.

This empirical form for the microwave supercurrent, j_μ, encouraged us to attempt to interpret these results in terms of the GL calculation of j_c. We found that if the decay length within the link $\xi_{s'}$ is assumed to be voltage dependent then an analytic fit to all of the microwave data can be obtained by a calculation similar to that indicated for j_c (i.e., Eqn. (1)). But, for this calculation $\xi_{s'}$ (Eqn. (2)) is replaced by a voltage dependent counterpart:

$$\xi_{s'}^2 = \xi_{s'}^2(0)\,[(t-1) + \alpha\, e\overline{V}/kT_{s'}]^{-1} \qquad (3)$$

Equation (3) differs from (2) by the parameter $\alpha\, e\overline{V}/kT_{s'}$ and reduces to Eqn. (2) at zero voltage. The parameter α was then evaluated by using Eqns. (1) and (3) to calculate j_μ and fitting the result to the data. We found that a single value for α ($\alpha = 0.3 \pm 0.05$) fit all of our data up to $\sim$4 GHz for all links. Note, that the substitution of Eqn. (3) into expression (1) for j_c requires that $B_0^{\,2}$ and B^2 are also functions of voltage. In the limit where $T_{s'} < T_s$, $B_0^{\,2}(V) = (T_s - T)/(T + 0.3\, e\overline{V}/k - T_{s'})$ while for $T_s \ll T_{s'}$, $B_0^{\,2}(V) = 0.33\, T_s/(T + 0.3\, e\overline{V}/k - T_{s'})$. $B^2(V)$ is determined by substituting the values of $\xi_{s'}(V)$ and $B_0^{\,2}(V)$ into the expression for B^2. The result of this calculation is effectively identical to the empirical expression, $j_\mu = j_c \exp(-\overline{V}/V^*)$ over the temperature range of the data.

Alternative analysis was also attempted along the lines of heating[12] and an RSJτ model[13] with much less overall consistency. Heating effects could be induced experimentally but were considerably smaller than the effects observed in this study at these frequencies and were functionally proportional to $(\overline{V})^2$ rather than $(\overline{V})$. For the RSJτ model, no single consistent fit to all of the data was possible over the entire range of experimental parameters.

Equations (1) and (3) were also used to analyze the step width as a function of applied microwave voltage and step number. Figure 3 shows data for the relative width of steps number $n = 0, 1$, and 2 induced in the I-V curve of a Ta/Hf link ($L = 0.5\ \mu m$) at 4 GHz. Critical current was $\sim 20\ \mu A$; similar results were found for other currents and links as long as $T > T_{s'}$ and $\hbar\omega > 2eI_cR$. A comparison is made in Fig. 3 between a simple RSJ model (dashed line) and a RSJ model using a voltage dependent $j_\mu(\bar{V})$ (solid line) as found from Eqns. (1) and (3). These results indicate that $j_\mu(V)$ is capable of describing the detailed functional dependence of step size in this frequency range.

Thus, it appears that the apparent voltage dependence of j_μ can be analytically related to a modification of decay length $\xi_{s'}$ as indicated by Eqn. (3). The usual interpretation of decay length is in terms of pair lifetimes in S'. Consequently, we have used Eqn. (3) to infer the corresponding lifetime effects. This empirical form for the decay length $\xi_{s'}$ implies that, for $T > T_{s'}$, an additional pair breaking mechanism occurs in S' at finite voltages. An estimate of the pair lifetime τ_v associated with this process was obtained by writing $\xi_{s'}$ in terms of a diffusion constant $D = 1/3(v_f \ell)$ and an effective lifetime τ as $\xi_{s'} = \sqrt{D\tau}$. If two independent pair breaking effects are assumed, the usual thermal process and a voltage dependent process, then the effective lifetime can be written as $\tau^{-1} = \tau_\rho^{-1} + \tau_v^{-1}$, where τ_ρ is the usual thermal pair lifetime[14] $\tau_\rho = \pi\hbar/\pi k(T - T_{s'})$, and τ_v is associated with the additional voltage dependent process. By substituting Eqn. (3) (with $\alpha = 0.3$) for $\xi_{s'}$ in $D\xi_{s'}^2 = \tau_\rho^{-1} + \tau_v^{-1}$ and solving for τ_v leads to an empirical determination of τ_v. Following this procedure leads to $\tau_v = (\hbar/e\bar{V})$.

The basic experimental fact is that for $T > T_s$, the amplitude of the microwave Josephson current in these S/S'/S weak links appears to be voltage dependent as $j_\mu = j_c \exp(-\bar{V}/V^*)$, where j_c is the dc critical current. The voltage $\bar{V}$ is the RMS average voltage across the link and includes contributions from both the dc and microwave voltages. This relatively simple empirical result holds up to ~4 GHz. We are not aware of any theoretical explanation of these results and consequently have analyzed the results in terms of an effective voltage dependent decay length and a corresponding pair lifetime (or pair decay rate $R \equiv \tau^{-1}$). The numerical results of such an analysis is that the RMS voltage across the link contributes a term to the pair decay rate which is approximately equivalent to the average Josephson frequency.

One possible interpretation of this result is that for $T > T_s$, the pair decay rate in S' is augmented by the Josephson oscillation. The induced LY order parameter Ψ in S' (which was used to calculate j_c as in Eqn. (1)) assumes no such interference effects - only a thermal decay[14] - and linear superposition. However at finite voltage, $\Psi(S')$ is periodically quenched at the Josephson frequency. We propose that these experimental results suggest that this induced periodic quenching of $\Psi(S')$ is reflected in the pair lifetime - the maximum pair lifetime being limited to one Josephson cycle. In terms of decay rate, such an effect would add a contribution R(V) to the decay rate, $R(V) \approx 2eV/\hbar$. Correspondingly, up to ~4 GHz we find R to be augmented by $R(V) \approx e\bar{V}/\hbar$, as described herein. However, at higher frequencies and lower temperature this simple (adiabatic) relationship between R(V) and the RMS voltage $\bar{V}$ breaks down. For frequencies >10 GHz, the step size was observed to become a complicated function of frequency and temperature for which j_μ was, under some conditions, larger than j_c. Furthermore, the critical current, j_c can also be increased[3] dramatically as in the Dayem-Wyatt effect. These complications (presumably due to quasiparticle excitation) are still under investigation.

Conclusions

A detailed examination of the dc critical supercurrent density, j_c, and the microwave supercurrent density, j_μ, has been undertaken for S/S'/S thin film weak links. The data and analysis reported herein refer mainly to the temperature range $T > T_{s'}$. In the steady state, j_c is found to be adequately described by a one dimensional Ginzberg-Landau formalism similar to that of Likharev and Yakobson but with De Gennes boundary conditions on the order parameter applied at each S/S' interface. An experimental examination of the microwave supercurrent indicates that j_μ is an exponentially decreasing function of increasing voltage up to $\sim$4 GHz. The amplitude of the microwave supercurrent, j_μ, was empirically determined to be $j_\mu = j_c \exp(-\bar{V}/V^*)$ where $\bar{V}$ is the RMS voltage $\bar{V} = [(nV_0)^2 + 1/2\, V_\mu^2)]^{1/2}$ and V^* is a length dependent constant, $V^* = 10^{-5}\, L^{-1}$ (μm). This effect has been interpreted in terms of an interference modulation of the pair density within S' at the Josephson frequency.

Acknowledgements

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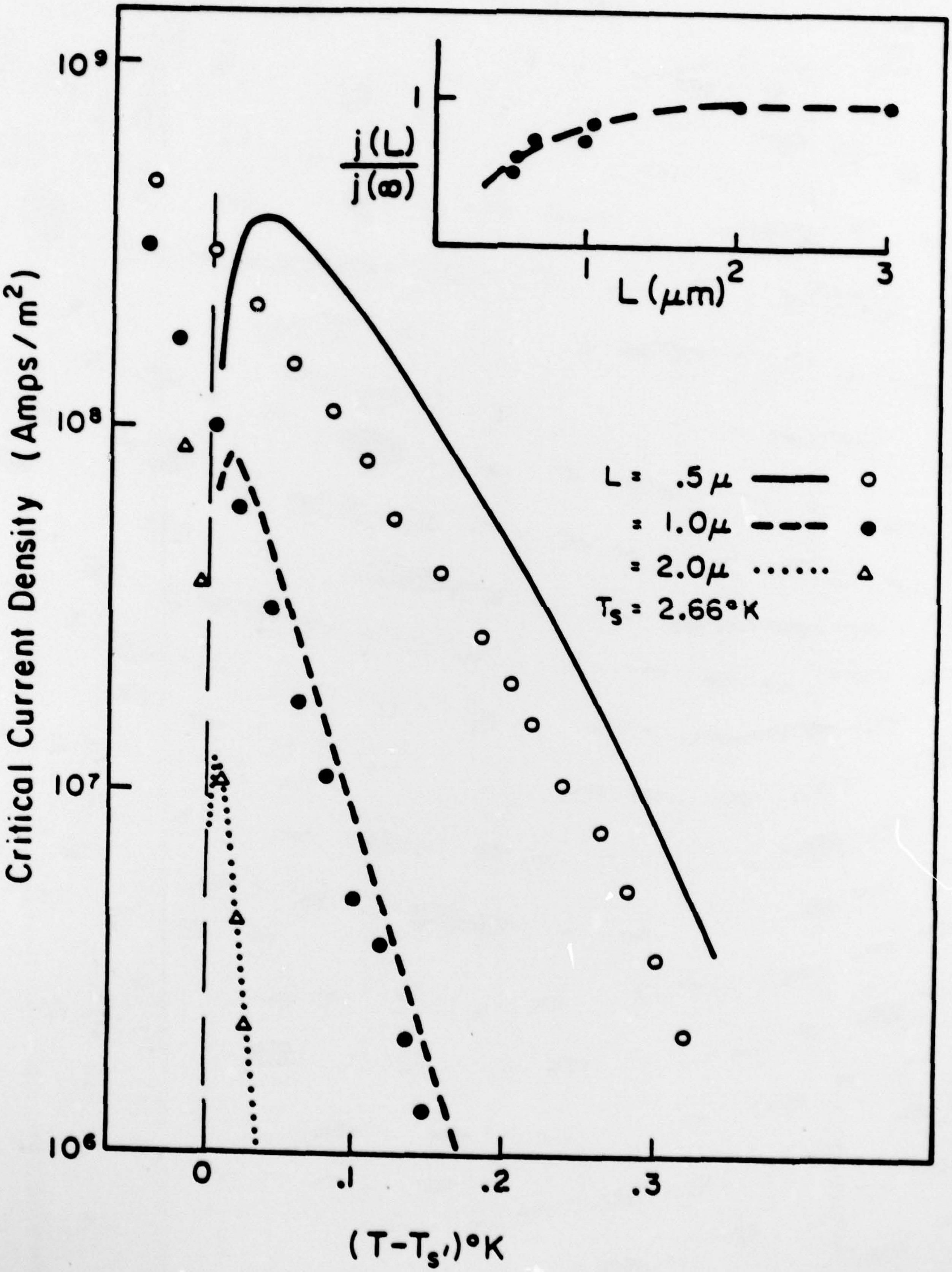
Figure Captions

Fig. 1 Critical current density j_c as a function of temperature and length. Insert shows relative decrease of j_c with length. Curves are calculated values from Eqn. (1).

Fig. 2 (a) Relative maximum amplitude of step $n = 1$ as a function of length and frequency. Curves are calculated from Eqns. (1) and (3). (b) Relative maximum step amplitude as a function of step number for $L = 0.5\ \mu$ at 4 GHz.

Fig. 3 Relative step amplitude ($n = 0, 1, 2$) as a function of microwave voltage. Dashed curve is calculated from RSJ model, full curve includes Eqns. (1) and (3).



10⁹
10⁸
10⁷
10⁶
Critical Current Density (Amps/m²)
0
.1
.2
.3
(T−Ts')°K
L = .5 μ
= 1.0 μ
= 2.0 μ
Ts = 2.66°K
j(L)/j(∞)
1
1
2
3
L (μm)

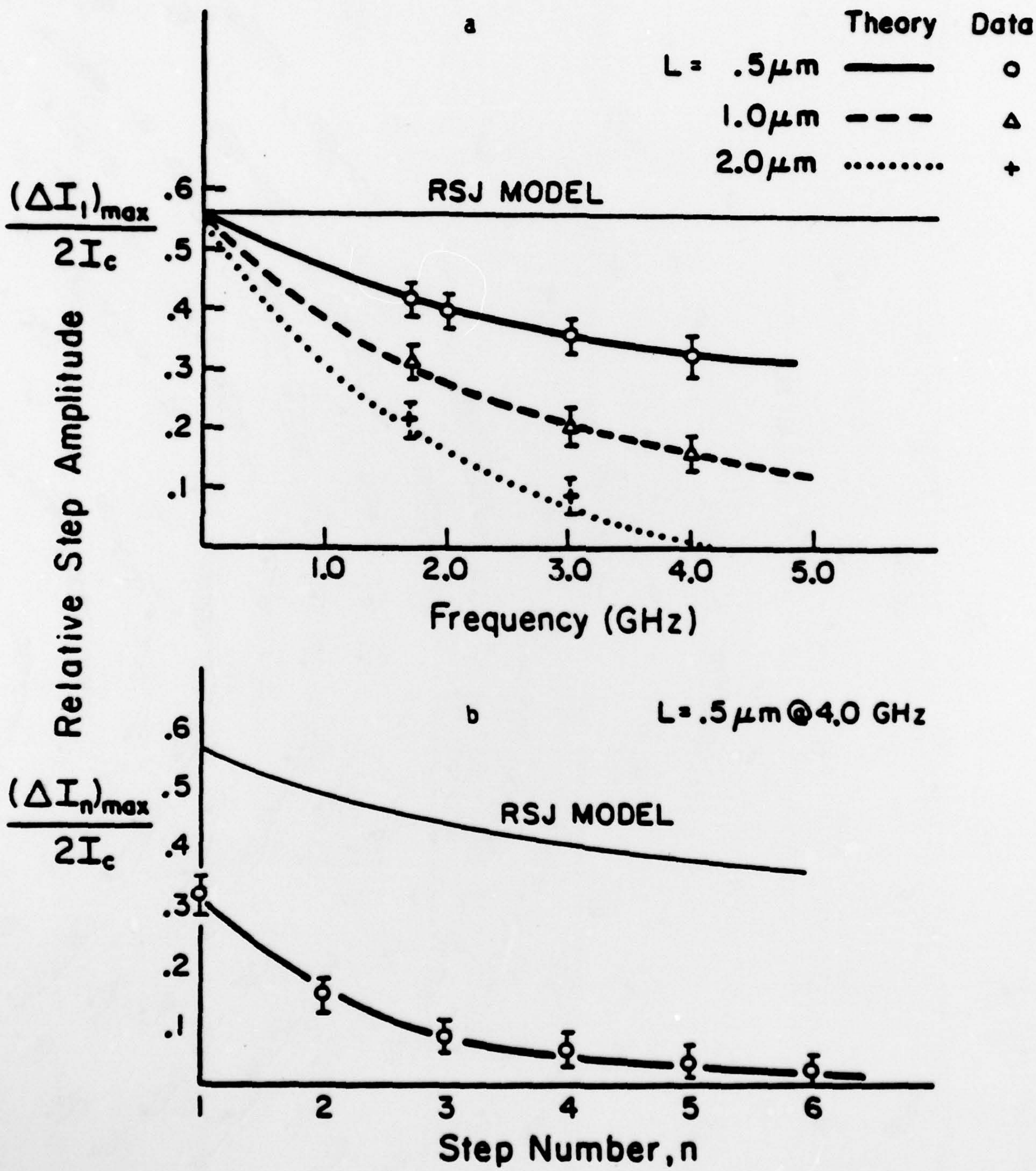

a
Theory
Data
L = .5μm
1.0μm
2.0μm
RSJ MODEL
$\frac{(\Delta I_1)_{max}}{2I_c}$
.6
.5
.4
.3
.2
.1
1.0
2.0
3.0
4.0
5.0
Frequency (GHz)
Relative Step Amplitude
b
L = .5μm @ 4.0 GHz
RSJ MODEL
$\frac{(\Delta I_n)_{max}}{2I_c}$
.6
.5
.4
.3
.2
.1
1
2
3
4
5
6
Step Number, n

Figure 2

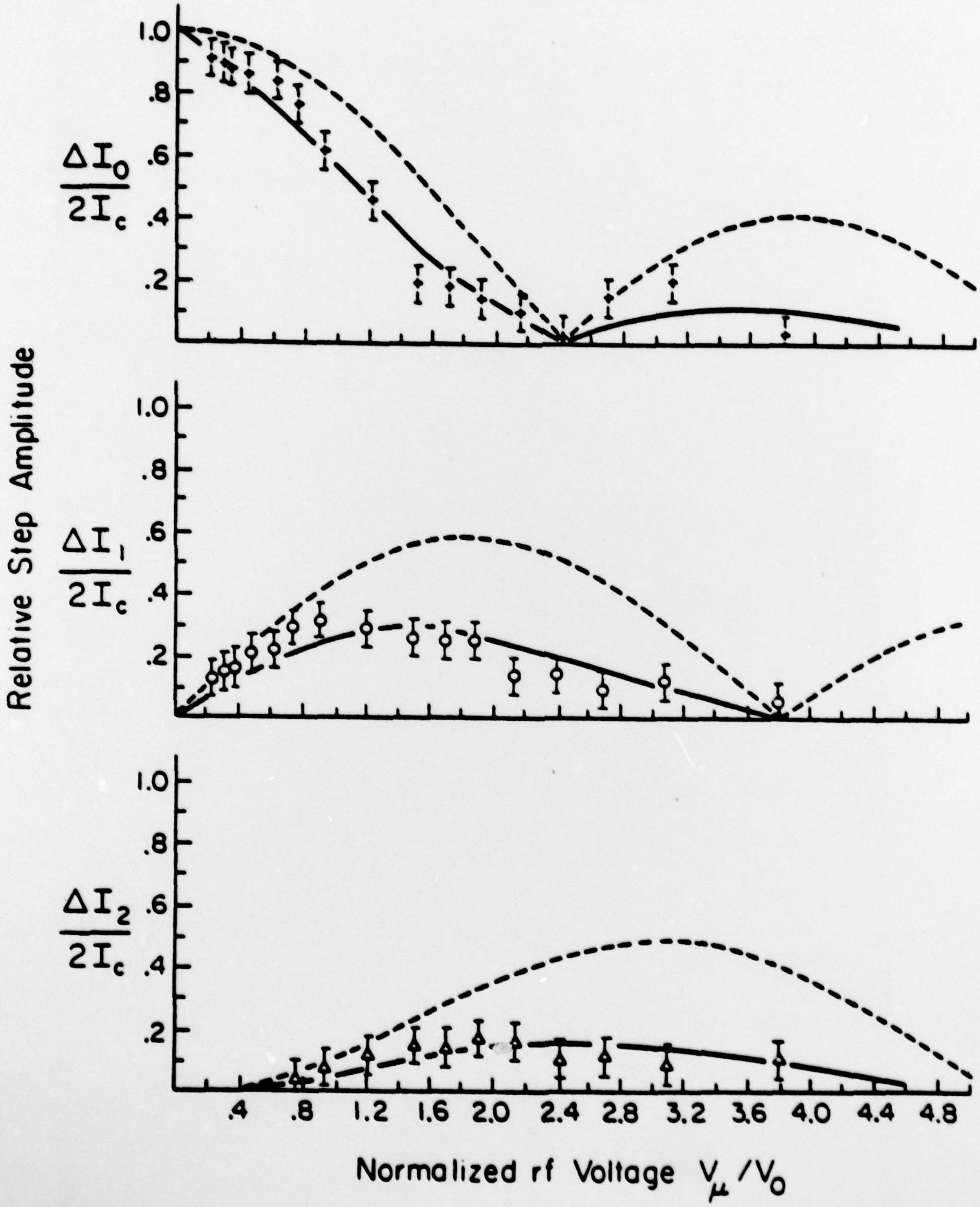

Relative Step Amplitude
$\frac{\Delta I_0}{2I_c}$
$\frac{\Delta I_1}{2I_c}$
$\frac{\Delta I_2}{2I_c}$
1.0
.8
.6
.4
.2
.4 .8 1.2 1.6 2.0 2.4 2.8 3.2 3.6 4.0 4.4 4.8
Normalized rf Voltage V_μ / V_0

Figure 3

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

9

REPORT DOCUMENTATION PAGE

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A detailed experimental examination of the dc critical supercurrent density, j_c (sub c), and the microwave (nonzero voltage) supercurrent, j_μ (sub mu), has been made in proximity effect thin film weak links at temperatures above the transition temperature of the link material. These results were correlated

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with measured dimensional and superconducting parameters of the thin films and the link via a Ginzberg-Landau (GL) formalism. In the steady state, j_c, was found to be adequately described by a one dimensional GL formalism similar to that of Likharev and Yakobson but with De Gennes boundary conditions on the order parameter applied at each interface. However, j_μ decreases exponentially with increasing voltage and can be interpreted in terms of an interference modulation of the induced pair density within the link at the Josephson frequency.

sub mu

sub c